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Greenhouse gas reductions through enhanced use of residues in the life cycle of Malaysian palm oil derived biodiesel

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Supplementary Data for

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Appendix 1

Brief background literature review

Studies carried out on environmental impacts from the production of palm oil and palm oil derived biodiesel have solely been focusing on the current practices in the production process without investigating the potential benefits of environmental improvements in the system, e.g. Schmidt (2007) and Choo et al., (2011). The current debate focuses largely on land use change, however, whereas land use change is a very significant focus area, it is not the only area, which can lead the way to sustainable palm oil.

Several studies exist on the waste quantities produced (e.g. Yusoff (2006)) and the various recycling technologies. Apart from the technologies described in Sections 3.1 – 3.6 in the main article, reuse of palm oil residues have been researched e.g. within bioethanol from EFB (Tan et al., 2010), citric acid from EFB (Bari et al., 2009) and POME (Alam et al., 2008), plywood/fibreboards from EFB and trunks (Khalil et al., 2010), and cellulose enzyme from EFB (Alam et al., 2009). However, only few of these mention the quantitative environmental impacts and benefits from the technology and none have investigated the actual benefits in a life cycle perspective. Thus, this study has chosen to focus on the existing technologies listed in Section 1 in the main article.

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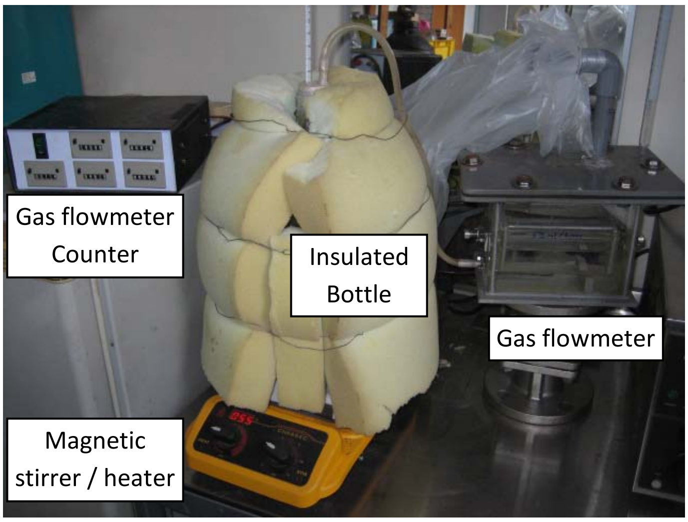
Appendix 2

Experimental set-up – Anaerobic digestion of EFB

The experiments were designed to provide indications of the biogas potential in fibrous solid palm oil residues. The shredded EFB from a palm oil mill were digested in a batch process, fully mixed, 52°C thermophilic digester for 21 days at a loading of 5% w/w. On day one of the experiments, 200 g shredded EFB were added to 4 L of thermophilic anaerobic bacteria solution ($MLSS_{bacteria} \approx 4{,}000$ mg/L) in an insulated 5 L glass bottle. The insulation was 5 cm thick sponge material. The anaerobic bacteria solution, which was retrieved from a Malaysian full scale batch process, fully mixed, thermophilic digester using POME as a feedstock, had been left to degrade all remaining organics for 5 days to ensure that gas produced during the experiments was from the EFB only. Using bacteria from a POME fed digester is considered the most representative solution, as the EFB will be co-digested with POME in a full scale scenario. The bottle (hereafter 'digester') was sealed to allow only for a gas tube and a thermometer and placed on a combined heater/magnetic stirrer. The temperature was maintained at a constant 52°C in the digester. Produced gas volumes were measured continuously using an unnamed flowmeter developed by Chiang Mai University for small gas volumes. The gas volumes were recorded daily to determine the degradation rate of the fibres (as depicted by the gas production) as a function of the hydraulic retention time, which is crucial for estimating the potential loading of fibres into a full scale biogas plant. The methane content of the biogas was analysed twice weekly using a Dräger X-am 7000 methane meter. After the 21 days the digester was opened and the digestate was analysed for nutrient values in order to assess potentials in application as fertilizer. The digestate and the remaining fibres were separated and the liquid was analysed for total N , P and K using Standard Methods APHA[1] 4500-N_{org} B & 4500-NO_3^- H for total N, APHA 4500-P B&F for total P and APHA 3120 B for total P. The fibers were rinsed clear of bacteria sludge and analysed for Total N, P and K as well using APHA 4500-N_{org} B & 4500-NO_3^- H for total N, and Acid digest / IPC for Total P and K.



[1] Standard Methods for Examination of Water and Wastewater, 21st Edition 2005, American Public Health Association

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Appendix 3

Overview of the waste quantities

Table A1 – Co-products and waste products in the biodiesel life cycle [kg (wet weight)/ton CPO]

	Stage	a	b	c	d	e	f	Average
Raw material								
Land	Plantation	0.26 ha	-	-	-	-	-	0.26 ha
Fresh Fruit Bunch, FFB	Plantation	4885	-	-	-	-	-	4885
Co-products								
Crude Palm Kernel Oil	Milling	120	-	-	-	-	-	120
Palm Kernel Cake	Milling	133	-	-	-	-	-	133
Palm Fatty Acid Distillate	Refining	45	-	-	-	-	-	45
Glycerine	Biodiesel	-	-	-	-	93	-	93
Total co-products								391
Waste Products								
Fronds	Plantation	-	-	2835	-	-	2573	2,700
Stems	Plantation	-	-	759	-	-	812	786
Empty Fruit Bunch, EFB	Milling	-	1014	1125	1168	884	1094	1,100
Press fibre	Milling	-	673	650	629	716	671	656
Boiler Ash	Milling	-	-	-	16	-	-	16
Palm Oil Mill Effluent , POME (liquid)	Milling	-	3290	3365	3045	3116	3328	3,250
Shells (palm kernel)	Milling	-	359	350	358	307	272	335
Spent Bleaching Earth	Refining	-	-	7	-	-	-	7

a. (MPOB, 2010)
b. (Felda, 2010)
c. (Schmidt, 2007)
d. (Subramaniam et al., 2008)
e. (Wicke et al., 2008)
f. (Yusoff, 2006)

MPOB (Malaysian Palm Oil Board) is the research body for the Malaysian palm oil industry. Their values for national production and co-products is considered as reliable. The waste products are not part of the annual statistics from MPOB, so external studies have been used. It is not possible to disqualify the values for the waste products from any of the studies above, so average values have been used.

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Spent bleaching earth is rich in oil residues and could potentially be added to a biogas plant. However, due to the small quantities and lack of available data, it was not included in this study.

Wastewater from the refineries and biodiesel plants is also relatively high in oil residues, however, the amounts are not expected to be high enough to have any significant impact on the GHG balance even if the wastewater is treated anaerobically with biogas capture and combustion in a gas engine.

Co-product allocation by mass

Products at mill: 1,000 kg CPO + 253 kg palm kernels ➔ 80% for CPO, 20% for Palm Kernels

Products at refinery: 1,000 kg CPO + 45 kg PFAD ➔ 96% for CPO, 4% for PFAD

Products at biodiesel plant: 1,000 kg CPO + 93 kg glycerine ➔ 91% for CPO, 9% for glycerine

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Appendix 4

Introduction to bio-char and yields from pyrolysis

Lim and Lim (1992) measured 30% volatile carbon in char from palm oil trunk at 400°C and 20% at 500°C, based on which this paper assumed 10% at 900°C. Since no such measurements are available for EFB and shells, the same values are assumed for these. In Table A2 it is assumed that all the volatile carbon degrades in the first few years. The volatile carbon has thus been subtracted from the total carbon of the char to get the fixed carbon. Quantitative studies on the improvement in yields due to application of bio-char in tropical soils have not been conducted. In the following it is assumed that the fertilizer savings and soil properties benefits are equal to those of EFB mulching. So at 10 g bio-char produced per kg EFB, 1 kg bio-char has the fertilizer value of 10 kg EFB equal to 140 g CO_2 in accordance with (PE International, 2006b).

Bio-char could be applied to the oil palm plantations at re-planting. This would ensure no char is lost due to surface run-off and it would require no additional man-power for application.

Studies on pyrolysis of oil palm residues and the use of the pyrolysis products are few and deliver inconsistent results. No data is available on energy input vs. output and on the feasibility of constructing and operating pyrolysis plants. In its Economic Transformation Programme initiated in 2010, the Malaysian government is emphasizing bio-oil as a desired product from the palm oil residues and targets a yearly production of 3.8 million tons bio-oil by 2020. Thus significantly more research can be expected within the area in the coming years. Since bio-char is co-produced with bio-oil, more research should be done within pyrolysis conditions, which can favour both bio-oil production and bio-char with a high degree of fixed carbon as well as research on bio-char application to soil.

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Table A2 – Yields from pyrolysis of palm oil wastes at various temperatures

	Temp.	Bio-char Yield		Bio-oil Yield		Net Gas Yields[g]	
	[°C]	[% of dry input]	C Content	[% of dry input]	LHV[e] [MJ/kg]	[% of dry input]	LHV[f] [MJ/kg]
Optimal Bio-char							
EFB[a]	~400	30%	40%	35%	20	15%	5
Shells[b]		40%	45%	40%	20	0%	5
Trunk[c]		35%	40%	40%	20	5%	5
Optimal Bio-oil							
EFB[a]	~500	25%	50%	40%	20	15%	5
Shells[b]		30%	55%	45%	20	5%	5
Trunk[c]		30%	50%	40%	20	10%	5
Optimal Gas							
EFB[a]	>900	5%	60%	10%	20	65%	15
Shells[b]		10%	70%	20%	20	50%	15
Trunk[c, d]		5%	60%	10%	20	65%	15

Data in the literature varies greatly due to various methods and assumptions. Data given is based on averages and may vary significantly from individual references.

a) based on (Sukiran et al., 2009); (Abdullah et al., 2010); (Abdullah and Gerhauser, 2008); (Sulaiman and Abdullah, 2011); (Li et al., 2007)

b) based on (Khor et al.,, 2010); (Li et al., 2007)

c) based on (Kim et al., 2010); (Lim and Lim, 1992);

d) no data available in literature. Data for EFB is used.

e) Inconsistent data in literature. 20 MJ/kg (Abdullah and Gerhauser, 2008) is used, which is consistent with (Mullen et al., 2010)

f) Calculated from gas composition in (Li et al., 2007) No data for palm oil wastes available in literature. Low temperature LHV corresponds to (Mullen et al., 2010) (pyrolysis of corn).

g) A gas quantity corresponding to 20% of the total yield is assumed for pyrolysis operation. The figures given are thus actual percentages minus 20.

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Appendix 5

Table 3 –GHG balances for the various wastes and technologies compared to hypothetical carbon neutral disposal

Waste Technology	Replaced Product(s)	Saved CO2-eq [g CO2/kg waste]	Waste Quantity Available [kg waste/ ton CPO]	Saved CO_2-eq [kg CO2/ ton biodiesel]
Stems				
Pyrolysis	C seq./diesel/elec.	260	786	230
EFB				
Mulch	Fertilizer	15	1100	-15
Incineration	Fertilizer	5		5
Incineration	Electricity / fertilizer	260		315
Incineration	Coal	510		615
Pyrolysis	C seq./diesel/elec.	360		435
Landfilling	-	-1,080		-1,290
Biogas	Elec. / fertilizer	280	160	50
Shells				
Incineration	Electricity	760	255	210
Incineration	Coal	1,480		410
Pyrolysis	C seq./diesel/elec.	1,130		315
POME				
Open lagoon	-	-310	3257	-1,090
Biogas plant	Electricity	50		175
Biogas plant	Shells - 100 kg	50		180

The contributions from fronds, fibres and the shells used in the mill boilers are not included as they do not constitute savings or emissions outside the boundaries of the palm oil mill. The 'Saved CO_2 eq.' values are savings compared a no-impact scenario in which all the carbon in the wastes simply turn to CO_2.

Appendix 6

Background for setup of the conventional scenario

Table A3 (first part of Table 4 in the main article)

	Trunks	Fronds	EFB	Shells	Fibre	POME	Total
Boiler Fuel	-	-	-	50%	80%	-	
Mulch	100%	100%	75%	-	-	-	
Incineration	-	-	10%	-	-	-	
Industrial Use	-	-	5%	35%	15%	-	
Landfill	-	-	5%	15%	5%	-	
Compost	-	-	5%	-	-	-	
Open lagoons	-	-	-	-	-	95%	
Biogas	-	-	-	-	-	5%	

Boiler Fuel

In accordance with (Subramaniam et al., 2008) 520 kg of fibre and 170 kg shells are used in the mill boilers per ton CPO. Comparing these to the total quantities in Table A1 gives 80% and 50% respectively.

Mulch

Almost all trunks are still buried at the plantations. In order to limit the number of entries in the scenario, it has been listed as mulch and the benefits (fertilizer savings and soil improvement) are assumed to be similar to mulch from EFB (1 kg trunks = 1 kg EFB). This simplification does not have significant impact on the overall emissions from the current scenario.

All fronds are currently used as mulch (frond stacks) in the plantations. The benefits (fertilizer savings and soil improvement) are assumed to be equal to mulch from EFB (1 kg fronds = 1 kg EFB).

Incineration

Incineration of EFB without energy recovery is practiced at the mills in order to limit the weight and volume of EFB before applying as fertiliser. The practice is declining due to increased focus on air pollution from the simple incinerators.

Industrial Use

A small amount of EFB is use in industrial applications such as fibre boards and for incineration with energy recovery. In the quantification of GHG savings all 5% was allocated to Incineration with energy.

There is a rising trend in use of shells in industry boilers and in concrete production. All shells for industrial use have been allocated for use in industry boilers in the GHG calculations.

Some fibres are currently used in industry boilers or as a source of fibres in e.g. fibre boards. In the calculations, values for EFB incineration in industry boilers have been used.

Landfill

Only very limited landfilling of EFB is taking place and the practice can be expected to decrease further.

Excess Shells from remote mills are still landfilled as there are no uses for them on site and transportation to industries is not feasible. However, the hard shells are considered inert in a landfill.

As for the shells, some fibres at remote mills are landfilled. GHG emissions are assumed equal to EFB (1 kg fibre = 1 kg EFB).

Compost

Composting is practiced at some mills and is getting more common. It ensures that the nutrients in the EFB are made available to the palms, so in the calculations the benefits of compost is assumed double that of mulch (1 kg EFB for composting = 2 kg EFB for mulching).

Open lagoons and biogas

More and more biogas plants are being constructed. However, most of them flare off the biogas without energy recovery. Thus, in the conventional scenario, ‘Biogas’ is considered CO_2-neutral.

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Appendix 7

Sensitivity & Uncertainty

The uncertainty/sensitivity analysis is performed qualitatively in the following and presented quantitatively in Table A4.

Mill boilers

The mill boilers in Malaysia are generally inefficient as efficiency is not prioritized with the surplus availability of fibres and shells, which until recently did not have market value. With the growing market value for shells it is very likely that some mills will upgrade their boiler systems. The uncertainty analysis tests a realistic 20% increase in boiler efficiency in the prospective scenario, which will make the fibre alone able to meet the energy requirements, thus making the remaining 80 kg shells available for other applications. In the best case prospective scenario in Figure 3 in the main article, these 80 kg shells are treated as per the prospective scenario in Table 3 in the main article.

Mulch

The uncertainty analysis investigates the potential situation that the actual methane and N_2O emissions from mulch are negligible and the potential situation that the N_2O emissions are as per the (IPCC, 2006) default values for composting. Both situations are borderline realistic. Unpublished studies claim that N_2O emissions from Malaysian agricultural soil is significantly lower than the IPCC values, so the same could apply to the degrading EFB and the single layer EFB mulch is not unlikely to retain aerobic conditions. On the other hand, as the actual emissions have not been studied, it is also relevant to relate to the IPCC default values. Thus, the bandwidth of the GHG data when EFBs are applied as mulch varies from a net GHG reduction of 14 kg CO_2-eq/ton CPO due to the industrial fertilizer savings if the methane and N_2O emissions are negligible to emissions of 180 kg CO_2-eq/ton CPO if the IPCC default emissions apply. In this context any variations in the actual amount of industrial fertilizer replaced becomes insignificant as it would only contribute by a few kg CO_2-eq/ton CPO.

The sensitivity analysis also assumes that the fronds and the chipped trunks behave similarly to the EFB when it comes to methane and N_2O emission. The fronds and stems actually have higher nitrogen content than the EFB (Chow et al., 2008), so the emissions from these could be even larger than for EFB. Due to the large quantity of fronds, these become a major contributor of emissions in the worst case scenarios with over 400 kg CO_2-eq/ton biodiesel after allocation. Thus, especially the N_2O emissions from degrading fronds are important to study. It must, however, also me taken into consideration, that the mulch increases soil carbon (carbon sequestration) and soil fertility, which can give significant counter weight to the N_2O emissions. This must be researched further as well in order to achieve a balanced assessment.

Anaerobic treatment

There is little uncertainty in the methane emissions from POME, which are well documented.

However, for the landfilled EFB, it is not unlikely that the percentage of C being converted to methane could differ. A bandwidth was established assuming 15% and 25% C conversion to methane resulting in an emission range from 890-1480 kg CO_2-eq/ton CPO.

Biomass power

The GHG reductions can be considered as best case scenario for power production from the residues. IPCC (2006) suggests that app. 5 g CH_4/ton waste and 50 g N_2O/ton waste is likely to be emitted during incineration. This would reduce the GHG reductions from power production from EFB by just 4% and shells by 1%.

Biogas

Energy recovery from the remaining digested EFB has not been scientifically quantified, but preliminary calculations assuming that the dry weight calorific value of the digested EFB is the same as for fresh EFB have been made for the uncertainty analysis. These show that by substituting shells in the mill boiler and use these shells as per the prospective scenario in Table 3 in the main article, the GHG reductions from producing biogas from EFB could be doubled to a best case value of 89 kg CO_2eq/ton CPO. Conversely, it is not unlikely that a poorly managed biogas plant may have methane leakages of up to 10%, which would create a worst case GHG reduction value of 13 kg CO_2/ton CPO.

Pyrolysis

The three pyrolysis set-ups all give similar GHG reduction, which is to be expected since they are variations of the same process and using the same feedstock. Using the average value is likely to be a deviation from actual conditions, so in the uncertainty analysis, the double standard variations of the mean values for EFB, shells and trunks respectively have been used to create a potential bandwidth for the three residues: 362-433 kg CO_2-eq/ton CPO for EFB 253-323 kg CO_2-

eq/ton CPO for shells and 180-239 kg CO_2-eq/ton CPO for trunks. Using the double standard deviation takes into consideration that there are uncertainties in the mean value as well as in the individual set-ups.

Scenarios

The values in Table A4 are computed into the conventional and prospective scenarios in Table 3 in the main article to create best case and worst case scenarios.

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Table A4 – Quantitative uncertainty/sensitivity values

	New emission/reduction		Comment	Change
	kg CO2-eq/ton CPO	g CO2-eq/kg residue		
Mill boiler	255 kg shells available		default	
15% increased efficiency	335 kg shells available		best case	131%
Mulch (EFB)	-14	-12	default	
No CH_4 and N_2O emissions from mulching	14	13	best case	NA
IPCC default CH_4 and N_2O emissions from mulching	-198	-180	worst case	-1447%
EFB landfilling	-1184	-1077	default	-
25% c conversion to methane	-1480	-1346	worst case	125%
15% C conversion to methane	-888	-808	best case	-25%
Power production (EFB)	427	388	default / best case	-
5g/ton CH_4 emissions and 50g/ton N_2O emissions	410	372	worst case	-4%
Power production (shells)	285	1117	default / best case	-
5g/ton CH_4 emissions and 50g/ton N_2O emissions	281	1101	worst case	-1%
Biogas (POME)	163	50	default / best case	-
5% CH_4 leakage	105	32	-	-36%
10% CH_4 leakage	47	14	worst case	-55%
Biogas (EFB)	44	275	default	-
5% CH_4 leakage	29	179	-	-35%
10% CH_4 leakage	13	83	worst case	-54%
Digested fibre substituting shells in mill boiler	89	556	best case	202%
Pyrolysis (EFB)	398	362	default	-
+ 2 Standard deviations	433	394	best case	109%
- 2 Standard deviations	362	329	worst case	9%
Pyrolysis (shells)	288	1129	default	-
+ 2 Standard deviations	323	1267	best case	112%
- 2 Standard deviations	253	991	worst case	12%
Pyrolysis (trunks)	210	267	default	-
+ 2 Standard deviations	239	304	best case	114%
- 2 Standard deviations	180	229	worst case	14%

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